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Phase stabilization of the amplitude dividing four-beam combined laser system using stimulated Brillouin scattering phase conjugate mirrors

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Abstract

The beam combination method using stimulated Brillouin scattering phase conjugate mirrors (SBS-PCMs) is a promising technique for a high energy and high power laser output operating with a high repetition rate. The two-beam combined system was previously demonstrated with an amplitude dividing method. A four-beam combined laser system with amplitude dividing method is demonstrated in this work, and the phase stabilization experiment of this system is performed using the self phase control and the long-term stabilization technique. The phase differences between the SBS waves are stabilized with $\lambda/30$ and the fluctuation of the four-beam combined output energy is 6.16% during 2000 shots (200 s).

Keywords: Beam combination; High energy laser; Long-term stabilization; Phase conjugate mirror; Phase control; Stimulated Brillouin scattering

INTRODUCTION

Application of Brillouin scattering methods have attracted great attention in recent years (Hasi *et al.*, 2007; Kappe *et al.*, 2007; Lontano *et al.*, 2006; Meister *et al.*, 2007; Ostermeyer *et al.*, 2008; Wang *et al.*, 2007; Yoshida *et al.*, 2007). A very prominent application is laser fusion energy (LFE), which requires very high energy and high power laser output of several megajoules in a few tens of nanoseconds with a high repetition rate around 10 Hz (Nakai & Mima, 2004). However, the current systems in high energy laser facilities, such as NHELIX (Schaumann *et al.*, 2005), PHELIX (Neumayer *et al.*, 2005; Kuehl *et al.*, 2007), PALS (Jungwirth, 2005; Batani *et al.*, 2007; Laska *et al.*, 2006; Torrisi *et al.*, 2008), and Vulcan Petawatt (Danson *et al.*, 2005), are operated with a low repetition rate or a single shot due to the thermal problems of the laser materials. The beam combination method using stimulated Brillouin scattering phase conjugate mirrors (SBS-PCMs) is a promising one for the high energy output with a high repetition rate (Kong *et al.*, 1997; 1999; Basov *et al.*, 1979; Rockwell & Giuliano, 1986; Valley *et al.*, 1986; Loree *et al.*, 1987; Bower & Boyd, 1998; Riesbeck *et al.*, 2001; Riesbeck & Eichler, 2007; Kappe *et al.*, 2007; Ostermeyer *et al.*, 2008). This beam combined system can resolve the thermal problems by combining beams of small energies after separate amplifications. Furthermore, the high quality output beam can also be obtained from the PCMs of this system, which compensate thermal distortions in the laser amplifiers by generating the phase conjugate waves.

The SBS wave of the PCM has a random phase because it is naturally ignited by thermal noise (Boyd *et al.*, 1990). For a coherent beam combined output with SBS-PCMs, therefore, the phase relations between the SBS beams should be locked. For this reason, many previous researchers developed their own techniques to lock the phase difference between SBS beams (Basov *et al.*, 1979; Rockwell & Giuliano, 1986; Valley *et al.*, 1986; Loree *et al.*, 1987; Bower & Boyd, 1998). However, their systems have a structural limitation when combining many beams, due to very complicated composition with large number of optical components. To overcome this limitation, Kong *et al.* (2004, 2005*a*, 2005*b*, 2005*c*) proposed the self phase control technique, which can independently lock and control the phases of SBS waves from each phase conjugate mirrors, with the simple composition of few optical components. Therefore, the

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output energy can be unlimitedly scaled-up by increasing the number of combined beams. In the previous works, the principle of the self phase control has been demonstrated theoretically as well as experimentally (Kong *et al.*, 2004, 2005*a*, 2005*b*, 2005*c*, 2005*d*, 2006*a*, 2007; Lee *et al.*, 2005; Ostermeyer *et al.*, 2008). In addition to the self phase control, the long-term stabilization technique has also been developed to compensate the slowly varying phase fluctuation due to the thermal convection of the liquid SBS material (Kong *et al.*, 2006*b*, 2007, 2008).

In this work, as a further development of the beam combined system, the four-beam combined laser system is constructed with the amplitude division, which splits the main-beam to sub-beams using beam splitters. And the phase stabilization experiment of this four-beam combined system is performed using the self phase control and the long-term stabilization technique.

EXPERIMENT

Figure 1 shows the experimental setup for the four-beam combined laser system using self phase controlled stimulated Brillouin scattering phase conjugate mirrors. A 1064 nm Nd:YAG laser (Spectra-Physics, Model #GCR-150) with a line width of ~120 MHz is used for a laser source of the four-beam combined system. This laser has a pulse repetition rate of ~10 Hz, a pulse width of ~8 ns, and a quasi-Gaussian beam profile with ~8 mm diameter. The beam from the laser initially has a *p*-polarization and passes through the first polarizing beam splitter (PBS). The quarter wave plate (QWP3) with its fast axis at −45° changes the linear polarization to a circular one so that the beam is divided into two parts with almost equal energies at the second PBS. Each divided beam is split into two parts by the PBS again after passing through the half wave plate (HWP1 or HWP2). Consequently, the initial beam is divided into four sub-beams with equal energies. The four sub-beams are reflected by four separated self phase controlled SBS-PCMs, and recombined again at the second PBS. The recombined beam goes to the output part and is reflected at the first PBS rotating its polarization by 90° with the help of the quarter wave plate (QWP3).

The self phase controlled SBS-PCMs used in the experiment is composed by a 300 mm long SBS cell and a concave mirror with a 150 mm focal length. The surface of the concave mirror is high reflection coated with >99% reflectivity. The initial phase of the SBS wave can be locked by just putting this concave mirror behind the cell as shown in Figure 2. In this arrangement, the front part of the incident pump pulse (rE_p), reflected at the concave mirror, interferes with the rest of the incident pump pulse (E_p). This interference generates the electro-magnetic standing wave inside the cell. The ignition position of the acoustic wave is determined to be one of the nodal points of the standing wave. Therefore, the phase of the acoustic wave can be locked while the phase difference between the nodal points is equal to integer times 2π. In the SBS cell, a heavy fluorocarbon liquid FC-75 (3M company) is used for the SBS generation. It is a well-known SBS material which gives high reflectivity and excellent fidelity (Yoshida *et al.*, 1997).

Regardless of the self phase controlled SBS-PCMs, there exist the long-term phase fluctuations of the SBS beams due to the thermally induced convection of the liquid SBS media. This slowly varying long-term phase fluctuation can be easily compensated by active control of piezoelectric translators (PZTs) attached at three concave mirrors except one reference SBS beam, after measurement of the phase relations between the SBS beams. In the two-beam combined arrangement, it is easy to obtain the phase relation between SBS beams using the interfered energy of them. Therefore, first of all, the neighbored SBS beam phases of each two-beam unit are adjusted to the same value by matching one to the other.

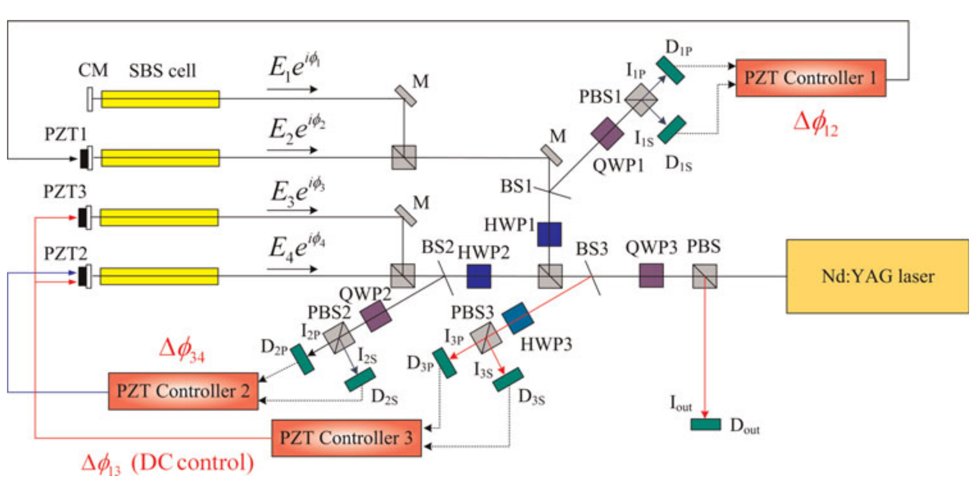

Fig. 1. (Color online) Experimental setup for the four-beam combination system with amplitude division: PBS, PBS1, PBS2, and PBS3; polarizing beam splitters, QWP1, QWP2, and QWP3; quarter wave plates, HWP1, HWP2, and HWP3; half wave plates, BS1, BS2, and BS3; beam splitters, D_{1P}, D_{1S}, D_{2P}, D_{2S}, D_{3P}, D_{3S}, and D_{out}; energy detectors, M; mirrors, CM; concave mirrors, PZT1, PZT2, and PZT3; piezoelectric translators.

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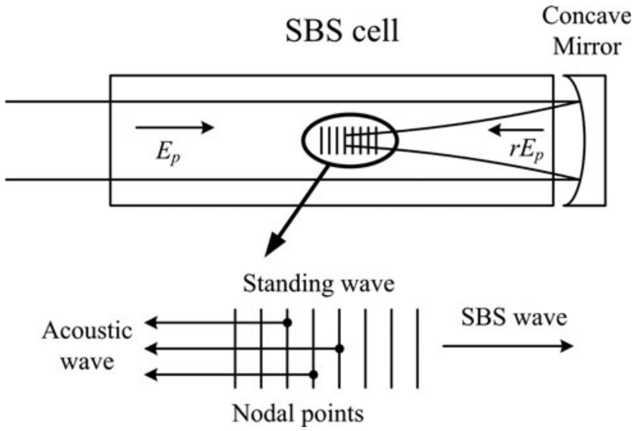

Fig. 2. Concept of phase control of the SBS wave by the self phase controlled SBS-PCM.

Numbering the four SBS beams to Beam1−4 from top to bottom for the convenient expressions, the four-beam system is considered as a combination of a two-beam unit of Beam1 and Beam2 and the other unit of Beam3 and Beam4. The phase of Beam2 can be matched to that of Beam1 by controlling PZT1 for every laser shot, after measurement of the phase relation between Beam1 and Beam2. This phase relation is obtained from the beam reflection at the beam splitter BS1, by measuring the transmitted and the reflected energies of the PBS1 using the pulse energy detectors (D_{1P} and D_{1S}) after passing through the quarter wave plate (QWP1) with its fast axis at 45°. By Jones matrix calculation, the electrical fields of the transmitted (E_{1P}) and reflected (E_{1S}) waves of the PBS1 can be obtained as,

$$\begin{pmatrix} E_{1P} \\ E_{1S} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \begin{pmatrix} r_1 E_1 e^{i\phi_1} \\ r_1 E_2 e^{i\phi_2} \end{pmatrix} = \frac{r_1}{\sqrt{2}} \begin{pmatrix} E_1 e^{i\phi_1} + E_2 e^{i(\phi_2+\pi/2)} \\ E_1 e^{i(\phi_1+\pi/2)} + E_2 e^{i\phi_2} \end{pmatrix}, \tag{1}$$

where E_1, E_2, ϕ_1, and ϕ_2 are amplitudes and phases of Beam1 and Beam2, respectively, and r_1 is the amplitude of the reflection coefficient of BS1. Then, the relation between the intensities of E_{1P} and E_{1S} and the phase difference ($\Delta\phi_{12} = \phi_1 - \phi_2$) of E_1 and E_2 is

$$I_{1P} = |E_{1P}|^2 = \frac{R_1}{2}\left(|E_1|^2 + |E_2|^2 + 2E_1E_2 \sin\Delta\phi_{12}\right) = \frac{R_1}{2}\left(I_1 + I_2 + 2\sqrt{I_1 I_2} \sin\Delta\phi_{12}\right), \tag{2}$$

$$I_{1S} = |E_{1S}|^2 = \frac{R_1}{2}\left(|E_1|^2 + |E_2|^2 - 2E_1E_2 \sin\Delta\phi_{12}\right) = \frac{R_1}{2}\left(I_1 + I_2 - 2\sqrt{I_1 I_2} \sin\Delta\phi_{12}\right), \tag{3}$$

where I_1 and I_2 are the intensities of E_1 and E_2, respectively, and R_1 is the reflectance of BS1. From Eqs (2) and (3), the following equation can be obtained

$$I_{ctrl1} = \frac{I_{1P} - I_{1S}}{I_{1P} + I_{1S}} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} \sin\Delta\phi_{12} = C_{12} \sin\Delta\phi_{12}. \tag{4}$$

I_{ctrl1}, calculated from I_{1P} and I_{1S} and measured by D_{1P} and D_{1S}, is used for the control signal of PZT1. PZT1 is controlled to make I_{ctrl1} equal to zero, so that $\Delta\phi_{12}$ goes to 0 and the phase of Beam2 is matched to that of Beam1. C_{12} is experimentally obtained by observing the changes of I_{ctrl1} during sufficiently long laser shots without control of PZT1. And the stabilized phase difference $\Delta\phi_{12}$ is obtained from measured I_{ctrl1} using C_{12} with the control of PZT1.

Similarly, after measurement of I_{2S} and I_{2P}, the PZT2 control signal I_{ctrl2} for matching the phase of Beam4 to that of Beam3 can be obtained from the following equation,

$$I_{ctrl2} = \frac{I_{2P} - I_{2S}}{I_{2P} + I_{2S}} = \frac{2\sqrt{I_3 I_4}}{I_3 + I_4} \sin\Delta\phi_{34} = C_{34} \sin\Delta\phi_{34}, \tag{5}$$

where I_3 and I_4 are the intensities of E_3 and E_4, respectively. C_{34} is experimentally obtained by observing the changes of I_{ctrl2} during sufficiently long laser shots without control of PZT2. And the stabilized phase difference $\Delta\phi_{34}$ is obtained from the measured I_{ctrl2} using C_{34} with the control of PZT2.

The electrical field of the recombined output of the two-beam units after passing through the QWP3 can be expressed as,

$$\begin{pmatrix} E_{3P} \\ E_{3S} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -i \\ -i & 1 \end{pmatrix} \begin{pmatrix} E_3 e^{i\phi_3} + E_4 e^{i\phi_4} \\ E_1 e^{i\phi_1} + E_2 e^{i\phi_2} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} (E_1 e^{i(\phi_1-\pi/2)} + E_2 e^{i(\phi_2-\pi/2)}) + (E_3 e^{i\phi_3} + E_4 e^{i\phi_4}) \\ (E_1 e^{i\phi_1} + E_2 e^{i\phi_2}) + (E_3 e^{i(\phi_3-\pi/2)} + E_4 e^{i(\phi_4-\pi/2)}) \end{pmatrix}. \tag{6}$$

Assuming that PZT1 and PZT2 are well-controlled so that $\Delta\phi_{12} = \phi_1 - \phi_2 \approx 0$ and $\Delta\phi_{34} = \phi_3 - \phi_4 \approx 0$, the four-beam combined output energy with *s*-polarization is

$$\begin{aligned} I_{out} &= \frac{1}{4}\left|(E_1 e^{i\phi_1} + E_2 e^{i\phi_2}) + (E_3 e^{i(\phi_3-\pi/2)} + E_4 e^{i(\phi_4-\pi/2)})\right|^2 \\ &\approx \frac{1}{4}\left|(E_1 + E_2)e^{i\phi_1} + (E_3 + E_4)e^{i(\phi_3-\pi/2)}\right|^2 \\ &= \frac{1}{4}\Big[\left(I_1 + I_2 + 2\sqrt{I_1 I_2}\right) + \left(I_3 + I_4 + 2\sqrt{I_3 I_4}\right) \\ &\quad + 2\left(\sqrt{I_1 I_3} + \sqrt{I_1 I_4} + \sqrt{I_2 I_3} + \sqrt{I_2 I_4}\right)\cos\left(\Delta\phi_{13} + \frac{\pi}{2}\right)\Big]. \end{aligned} \tag{7}$$

For maximizing the four-beam combined output energy, the phase difference between the output phase of one two-beam unit (Beam3 and Beam4) and that of the other two-beam unit

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(Beam1 and Beam2) is controlled to be $\pi/2$ by applying the appropriate direct current voltage to both PZT2 and PZT3, after measurement of the phase relation between Beam1 and Beam3. This phase relation is obtained from the beam reflection at the beam splitter BS3, by measuring the transmitted and the reflected energies of the PBS3 using the pulse energy detectors (D_{3P} and D_{3S}) after passing through the half wave plate (HWP3) with its fast axis at 22.5°. By Jones matrix calculation, the electrical fields of the transmitted (E_{3P}) and reflected (E_{3S}) waves of the PBS3 can be obtained as

$$\begin{pmatrix} E_{3P} \\ E_{3S} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} r_3 E_3 e^{i\phi_3} + r_3 E_4 e^{i\phi_4} \\ r_3 E_1 e^{i\phi_1} + r_3 E_2 e^{i\phi_2} \end{pmatrix} = \frac{r_3}{\sqrt{2}} \begin{pmatrix} (E_1 e^{i\phi_1} + E_2 e^{i\phi_2}) + (E_3 e^{i\phi_3} + E_4 e^{i\phi_4}) \\ -(E_1 e^{i\phi_1} + E_2 e^{i\phi_2}) + (E_3 e^{i\phi_3} + E_4 e^{i\phi_4}) \end{pmatrix}, \quad (8)$$

where r_3 is the amplitude of the reflection coefficient of BS3. The relation between intensities of I_{3P} and I_{3S} and the phase difference ($\Delta\phi_{13} = \phi_1 - \phi_3$) of E_1 and E_3 can be expressed as,

$$\begin{aligned} I_{3P} &= \frac{R_3}{2} \left| (E_1 e^{i\phi_1} + E_2 e^{i\phi_2}) + (E_3 e^{i\phi_3} + E_4 e^{i\phi_4}) \right|^2 \\ &\approx \frac{R_3}{2} \left| (E_1 + E_2) e^{i\phi_1} + (E_3 + E_4) e^{i\phi_3} \right|^2 \\ &= \frac{R_3}{2} \Big[\left(I_1 + I_2 + 2\sqrt{I_1 I_2} \right) + \left(I_3 + I_4 + 2\sqrt{I_3 I_4} \right) \\ &\quad + 2\left(\sqrt{I_1 I_3} + \sqrt{I_1 I_4} + \sqrt{I_2 I_3} + \sqrt{I_2 I_4} \right) \sin\left(\Delta\phi_{13} + \frac{\pi}{2} \right) \Big]. \end{aligned} \quad (9)$$

$$\begin{aligned} I_{3S} &= \frac{R_3}{2} \left| -(E_1 e^{i\phi_1} + E_2 e^{i\phi_2}) + (E_3 e^{i\phi_3} + E_4 e^{i\phi_4}) \right|^2 \\ &\approx \frac{R_3}{2} \left| -(E_1 + E_2) e^{i\phi_1} + (E_3 + E_4) e^{i\phi_3} \right|^2 \\ &= \frac{R_3}{2} \Big[\left(I_1 + I_2 + 2\sqrt{I_1 I_2} \right) + \left(I_3 + I_4 + 2\sqrt{I_3 I_4} \right) \\ &\quad - 2\left(\sqrt{I_1 I_3} + \sqrt{I_1 I_4} + \sqrt{I_2 I_3} + \sqrt{I_2 I_4} \right) \sin\left(\Delta\phi_{13} + \frac{\pi}{2} \right) \Big] \end{aligned} \quad (10)$$

where R_3 is the reflectance of BS3.

And the control signal I_{ctrl3} can be obtained from the following equation,

$$\begin{aligned} I_{ctrl3} &= \frac{I_{3P} - I_{3S}}{I_{3P} + I_{3S}} \\ &= \frac{2\left(\sqrt{I_1 I_3} + \sqrt{I_1 I_4} + \sqrt{I_2 I_3} + \sqrt{I_2 I_4} \right)}{\left(I_1 + I_2 + 2\sqrt{I_1 I_2} \right) + \left(I_3 + I_4 + 2\sqrt{I_3 I_4} \right)} \\ &\quad \times \sin\left(\Delta\phi_{13} + \frac{\pi}{2} \right) = C_{13} \sin\left(\Delta\phi_{13} + \frac{\pi}{2} \right). \end{aligned} \quad (11)$$

Measuring I_{ctrl3} from I_{3P} and I_{3S}, PZT2 and PZT3 are controlled to make I_{ctrl1} zero so that $\Delta\phi_{13} + \pi/2$ goes to 0 and I_{out} maintains a maximum value. C_{13} is experimentally obtained from observing the changes of I_{ctrl3} during sufficiently long laser shots without control of PZTs. And the stabilized phase difference $\Delta\ \phi_{13}$ is obtained from measured I_{ctrl2} using C_{13} with control of PZTs.

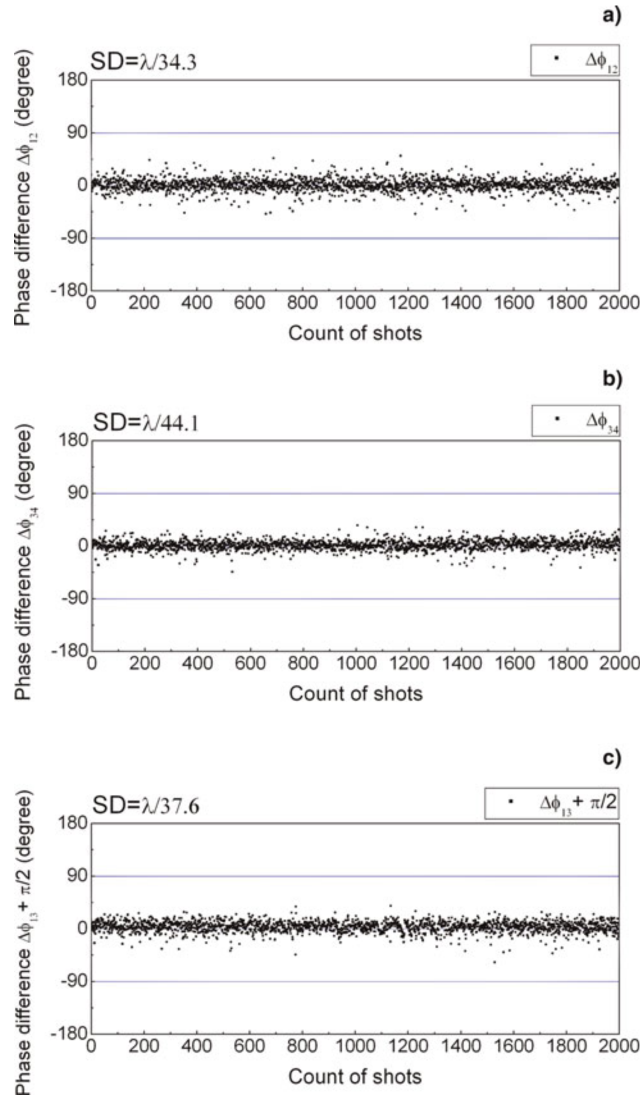

Fig. 3. Measured phase differences between the SBS beams during 2000 shots (200 s): (**a**) $\Delta\phi_{12}$, (**b**) $\Delta\phi_{34}$, and (**c**) $\Delta\phi_{13} + \pi/2$.

The experimental results of the phase differences ($\Delta\phi_{12}$, $\Delta\phi_{34}$ and $\Delta\phi_{13} + \pi/2$) using PZT controls are shown in Figure 3. The phase differences between the SBS waves are well-stabilized during 2000 shots (200 s). The standard deviations of $\Delta\phi_{12}$, $\Delta\phi_{34}$, and $\Delta\phi_{13}$ are measured to be $\lambda/34.3$, $\lambda/44.1$, and $\lambda/37.6$, respectively. Figure 4 shows the four-beam output energy during 2000 shots (200 s). The output energy is well-stabilized and the measured energy fluctuation is 6.16% by standard deviation. Although some abrupt energy drops are observed in the experiment, the output energies of 86.4% of the laser shots (1728 shots) are above 90% to the maximum value of all 2000 shots.

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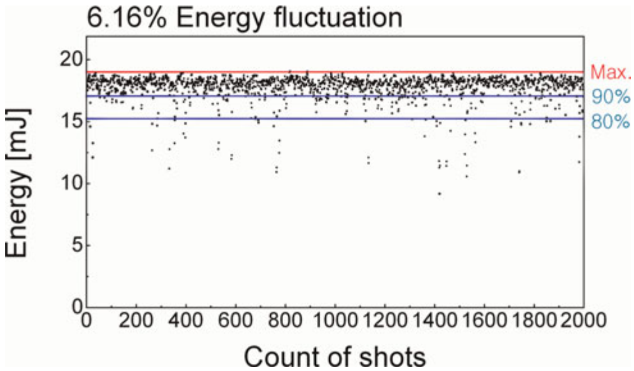

Fig. 4. (Color online) Four-beam combined output energy during 2000 shots (200 s).

CONCLUSION

In conclusion, the four-beam combined laser system is constructed with self phase controlled SBS-PCMs. For compensation of thermally induced long-term phase fluctuation, the PZTs are actively controlled by the concave mirror positions, so that all the phases of SBS beams are fixed at one reference. The phase differences between the SBS waves are well-stabilized with a standard deviation of less than $\lambda/30$ during 2000 shots (200 s) using the PZT controls. Finally, the stabilized four-beam combined output energy is obtained with 6.16% by standard deviation during 2000 shots (200 s). Infrequently, abrupt phase jumps are observed in this system. However, the output energies of 86.4% of the laser shots are above 90% of the maximum value of all 2000 shots.

This work of the four-beam combination is very meaningful, because it verifies that our beam combination can be extended to a many-beam combined system. The experimental setup, however, does not include the laser amplifiers and is just for the phase stabilizations of the four SBS beams. For demonstration of a practical beam combined system, optical amplifiers will be inserted to this four-beam combined system soon.

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